Climate change effects on the geographic distribution of specialist tree species of the Brazilian tropical dry forests

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Abstract

The aim of this study was to evaluate the ecological niche models (ENMs) for three specialist trees (*Anadenanthera colubrina*, *Aspidosperma pyrifolium* and *Myracrodruon urundeuva*) in seasonally dry tropical forests (SDTFs) in Brazil, considering present and future pessimist scenarios (2080) of climate change. These three species exhibit typical deciduousness and are widely distributed by SDTF in South America, being important in studies of the historical and evolutionary processes experienced by this ecosystem. The modeling of the potential geographic distribution of species was done by the method of maximum entropy (Maxent). We verified a general expansion of suitable areas for occurrence of the three species in future (c.a., 18%), although there was reduction of areas with high environmental suitability in Caatinga region. Precipitation of wettest quarter and temperature seasonality were the predictor variables that most contributed to our models. Climatic changes can provide more severe and longer dry season with increasing temperature and tree mortality in tropics. On this scenario, areas currently occupied by rainforest and savannas could become more suitable for occurrence of the SDTF specialist trees, whereas regions occupied by Caatinga could not support the future level of unsustainable (e.g., aridity). Long-term multidisciplinary studies are necessary to make reliable predictions of the plant's adaptation strategies and responses to climate changes in dry forest at community level. Based on the high deforestation rate, endemism and threat, public policies to minimize the effects of climate change on the biodiversity found within SDTFs must be undertaken rapidly.

Keywords: Caatinga biome, deciduous forest, ecological niche model, geographical species distribution.

Efeitos das mudanças climáticas sobre a distribuição geográfica de espécies arbóreas especialistas de florestas secas tropicais brasileiras

Resumo

Este estudo tem como objetivo avaliar a modelagem de nicho ecológico (ENMs) para três espécies especialistas (*Anadenanthera colubrina*, *Aspidosperma pyrifolium* e *Myracrodruon urundeuva*) de florestas tropicais secas (FTSs) no Brasil, considerando o cenário de mudanças climáticas: presente e futuro pessimistas (2080). Estas três espécies são decíduas e amplamente distribuídas pelas FTSs na América do Sul, sendo importante em estudos sobre os processos históricos e evolutivos experimentados por este ecossistema. A modelagem da distribuição geográfica potencial das espécies foi construída através do método de máxima entropia (Maxent). Foi observada uma expansão geral de áreas adequadas para a ocorrência das três espécies no futuro (cerca de 18%), embora tenha existido uma redução das áreas com alta adequabilidade ambiental na região da Caatinga. A precipitação do trimestre mais úmido e a sazonalidade da temperatura foram os fatores que mais contribuíram para os nossos modelos. As mudanças climáticas podem gerar períodos secos mais severos e longos, com aumento da temperatura e mortalidade de árvores em regiões tropicais. Neste cenário, as áreas atualmente ocupadas por florestas úmidas e savanas poderiam tornar-se mais adequadas para a ocorrência das árvores especialistas em FTSs, enquanto que as regiões ocupadas por Caatinga não poderiam suportar o nível futuro da não adequabilidade (por exemplo, aridez). Estudos multidisciplinares de longa duração são necessários para fazer previsões confiáveis de estratégias adaptativas das plantas e respostas às variações climáticas em FTS em nível de comunidade. Com base na elevada taxa de desmatamento, endemismo e ameaça, políticas públicas para minimizar os efeitos das mudanças climáticas sobre a biodiversidade encontradas dentro FTSs devem ser realizadas rapidamente.

Palavras-chave: bioma Caatinga, floresta decídua, modelagem de nicho ecológico, distribuição geográfica das espécies.

1. Introduction

The study of the impacts on biodiversity provoked by climate changes is not a new theme in the scientific literature (Parmesan, 2006; Phillips et al., 2010; Liu et al., 2013), but in last decade global climate changes reached great notoriety, notably in the popular press. In this way, we acknowledged that have a propitious moment to examine how global climate changes can affect species distribution (Peterson and Kluza, 2005). Considering the changes predicted by the Intergovernmental Panel on Climate Changes (IPCC, 2007), with likely increases in mortality of tree species and desertification in some arid regions (e.g., Caatinga region), it is very important to consider the consequences of indirect anthropogenic actions on the potential distribution of tree species (Colombo and Joly, 2010), especially in threatened or poorly studied tropical ecosystems.

Seasonally dry tropical forests (SDTFs) deserve attention within the scope of global warming because of their highly threatened conservation status, as well as the scant number of studies about their flora and ecology (Miles et al., 2006). Currently, there are about 1,048,700 km^2 of SDTFs in the world (Miles et al., 2006). The two largest continuous areas of this vegetation type are located in South America: one in northeastern Brazil (e.g., Caatinga region), and the other covering southeastern Bolivia and Paraguay and northern Argentina (Miles et al., 2006; Portillo-Quintero and Sánchez-Azofeifa, 2010), and these two sites represent 54.2% of the total area of remnant SDTFs in the world (Miles et al., 2006). These forests are dominated by deciduous trees with average annual temperature $\geq$ 25 °C, the total annual rainfall ranges between 700 and 2000 mm, and there is a minimum dry period of three months (rainfall < 100 mm/month) (Sánchez-Azofeifa et al., 2005). Severe climatic changes are predicted to occur between 2040 and 2069 in South America, and likely will affect the distribution of seasonal ecosystems due to increases in aridity (Miles et al., 2006), reinforcing the urgency of studies in order to determine the potential distribution of Brazilian SDTFs.

Global climate changes like to have important effects on biodiversity and ecosystem processes (Buytaert et al., 2011), and will undoubtedly affect species distribution and their biological traits (Santos et al., 2014). Several forecasts on climatic changes emphasize a longer and more severe dry season with a general increases in global temperature and tree mortality (IPCC, 2007; Buytaert et al., 2011), and feasible reduction of some STDF areas, including the Caatinga region. A tool often used to forecast geographical distribution is the ecological niche model (ENM), in which considers a wide range of climatic variables that characterize the tolerance limits of the species to such conditions, and applies on different climate projections to predict species distribution (Peterson and Kluza, 2005; De Marco Júnior and Siqueira, 2009). These models can provide detailed information about the suitability for geographical distribution of most species when interpreted in the context of ecology (Peterson and Kluza, 2005). In this study, a niche was considered to represent a set of tolerance limits in a multidimensional space that defines where a given species is potentially able to maintain its population levels (Grinnell, 1917), and a precise knowledge of these conditions can be used to predict favorable places to the occurrence of that species (De Marco Júnior and Siqueira, 2009).

Due to climatic alterations recorded in the last one hundred years (Araújo and Rahbek, 2006), the present study sought to evaluate the ENM of three specialist trees of SDTFs in Brazil (*Anadenanthera colubrina* (Vell.) Brenan, *Aspidosperma pyrifolium* Mart. and *Myracrodruon urundeuva* Allemão), considering present and future pessimist scenarios (2080) of climate changes. Based on climatic conditions predicted by the IPCC for the year 2080, as a longer and more severe dry season, and higher global temperature, the following questions were addressed: (i) How will climate changes affect the potential distribution of these typical species of SDTFs? (ii) Among the climatic variables (e.g., changes in precipitation and temperature seasonality), which the most important to ENM of these species?

2. Material and Methods

2.1. Data sources

A survey on species occurrence in SDTFs was undertaken by records of several herbaria in Brazil available at the Species Link site (Species Link, 2012). Data were compiled on the occurrence of three tree species considered to be widely dispersed SDTF's specialists in Brazil (see Linares-Palomino et al., 2011; Santos et al., 2012). We found 900, 860, and 700 occurrence records that were compiled for them throughout Brazil, respectively for *A. colubrina* (Fabaceae), *A. pyrifolium* (Apocynaceae) and *M. urundeuva* (Anacardiaceae). All three species demonstrate phenotypes typical of SDTFs and have been highlighted as important taxon in terms of studies concerning the historic and evolutive processes experienced by SDTFs in South America (Werneck et al., 2011; Collevatti et al., 2013).

Climatic variables were obtained from the WorldClim database (spatial resolution of 30 arc seconds; approximately 1 km^2). In order to avoid colinearity, we selected only environmental variables considered biologically relevant to species distribution and with low correlated values. As such, nine environmental variables available in the WordClim databank were selected, in addition to altitude (Table 1).

2.2. Data analysis

The ENM was undertaken using the maximum entropy method (Maxent) (Phillips et al., 2006). The model was created based on a set of bioclimatic variables projected onto a current scenario and confronted with a future (pessimistic) scenario in order to generate predictions

Table 1. Contributions to the ordination of environmental variables by the ecological niche model (using Maxent) and the estimated parameters by the GWR model.

Variable	Description	Maxent Contribution (%)	GWR		
			Coeff.	t	*P*
Intercept	-	-	0.605	10.394	<0.001
BIO 16	Precipitation of wettest quarter	53.4	–611.789	–6.951	<0.001
BIO 4	Temperature seasonality	22.5	–1771.147	–7.132	<0.001
BIO 14	Precipitation of driest month	7.9	22.093	3.293	0.001
BIO 15	Precipitation seasonality	7.2	–107.001	–10.141	<0.001
BIO 7	Temperature annual range	3.6	–49.965	–3.122	0.002
BIO 11	Mean temperature of coldest quarter	1.9	172.941	11.821	0
BIO 17	Precipitation of driest quarter	1.2	40.636	1.5	0.134
BIO 10	Mean temperature of warmest quarter	1	132.552	11.145	0
Alt	Altitude	0.9	–2163.279	–8.464	<0.001
BIO 3	Isothermality	0.4	–7.508	–2.262	0.024

for the potential distributions of SDTFs in the year 2080. Additionally, the contributions of each bioclimatic variable to the environmental suitability were evaluated. We concomitantly prepared a general ENM with occurrence of the three specialist species grouped in an attempt to identify patterns of the effects of climate changes on future SDTFs distribution. The occurrence datasets for ENM were generated from all presence points (2460) randomly selected from the entire distribution of the three specialist species, following recently proposed protocols for STDFs (Werneck et al., 2011). We trained Maxent model under present climatic scenario based on 1845 occurrence records (75%) randomly selected from the original 2460 occurrence points, and used the remaining 615 occurrence records (25%) to test the model.

In order to determine which climatic variables demonstrated the greatest influence (i.e., in terms of environmental suitability) on the ENM of the three specialist species, multiple regression model was performed. The variables that would be used in this analysis were selected using Akaike information criteria (AICc; Fotheringham et al., 2002). In general, environmental variables utilized in ENM are spatially autocorrelated, and statistical analyses that do not take this autocorrelation into account will incur Type I errors (Legendre and Legendre, 2003). The effect of each climatic variable on the ENM was quantified using geographically weighted regression (GWR) (Fotheringham et al., 2002). The spatial autocorrelation on GWR model was examined through the spatial structures of the residuals, utilizing Moran's I coefficient (Legendre and Fortin, 1989). All analyses were performed using SAM 4.0 software (Rangel et al., 2010).

3. Results

Brazilian SDTFs currently show wide distributions, with discontinuous areas on several biomes (Figure 1a), and most suitable areas to the occurrence of the three species evaluated here are concentrated in the northeastern region of the country (e.g., Caatinga region). The general ENM presented high reliable results (AUC = 0.89), with powerful accuracy in extrapolating of our results. Based on the model prediction, suitable areas for occupation of SDTFs specialist trees will expand in the future (2080), affecting the distribution of these forests over large humid areas of Brazil, principally in the northern (e.g., the states of Roraima, Rondônia, Amapá, Amazonas and Pará), central-western (e.g., Tocantins, Mato Grosso and Goiás), and the western part of the northeastern region of that country (e.g., Maranhão) (see Figure 1b). The map of the ENM in the future (2080) shows that suitable areas for the occurrence of these SDTFs species will increase by approximately 183,000 km^2, which is equivalent to 18% of their original area of distribution in Brazil (Figure 1). On the other hand, large extensions of areas with environmental suitability for the occurrence of SDTFs specialist trees in the semiarid northeastern region (e.g., Bahia, Sergipe, Alagoas, Pernambuco, Paraíba, Rio Grande do Norte and Ceará) and northern parts of Minas Gerais and Paraná could become reduced or completely lost by 2080 (Figure 1).

Based on AICc model selection, the full model showed better *goodness-of-fit*. The environmental variables that most contributed to the ENM are listed in Table 1. Based on our modeling, we identified precipitation of wettest quarter and temperature seasonality as the predictor variables that most contributed to the Maxent model. Likewise, related to GWR both these variables were significant and negatively related to the environmental suitability to occurrence these three species. All variables from GWR were statistically significant, except bio17 (Table 1). The global Moran's I analysis of model residuals from GWR confirmed the non-significant spatial autocorrelation (Moran's I = 0.003; p = 0.98).

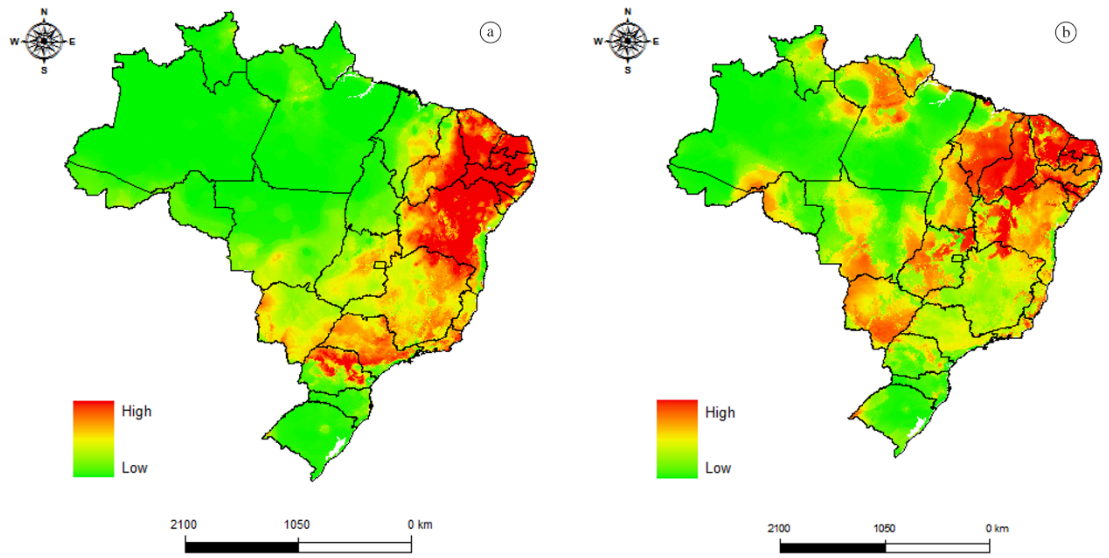

Figure 1. Maps of the ecological niche modeling of three Brazilian dry tropical trees projected for (a) present and (b) future climatic scenarios (2080), utilizing the maximum entropy algorithm (Maxent).

4. Discussion

Ecological niche modelling has been widely experienced to delimit species distribution potential in recent years (Peterson and Kluza, 2005; Werneck et al., 2011; Weber and Grelle, 2012; Collevatti et al., 2013). In general, our study demonstrated a potential expansion of the suitable environments for Brazilian SDTFs specialist trees in future climatic scenario (c.a. 18% of their current distribution), with a tendency to expand into areas that are currently occupied by savannas and humid forests (e.g., tropical rainforests), although some areas into of these regions currently are already SDTFs enclaves. We verified high congruence between ENM model for present climatic scenario and location of 187 sites of SDTFs used in the floristic analyses in northeastern, southeastern and central Brazil by Santos et al. (2012), reinforced the accuracy of the our model.

The variables precipitation of wettest quarter (i.e., mostly total rainfall at the beginning of the rainy season) and temperature seasonality had the strongest effects on the ENM. Although this vegetation type can tolerate numerous months with very dry and harsh environmental conditions, it does requires minimal access to water resources, with at least a few months of seasonal rainfall (Mooney et al., 1995; Sánchez-Azofeifa et al., 2005). This limited rainy period is crucial to photosynthesis, growth and resource allocation to reproduction (e.g., flowers and fruit production) (Mooney et al., 1995). Marengo et al. (2009) hypothesized that higher temperatures and longer dry seasons should have negative impacts on the geographic distribution and environmental integrity of these forests, although these variables appeared to have little weight in the prediction of species distributions in our model.

Climate changes provoked by human activities can to result in severe losses of biodiversity in many forest types (Miles et al., 2006; Moutinho, 2006). The main factors driving these losses are forest fragmentation, increasing incidences of forest fires, conversion of forest areas to agriculture use, and alterations in forest functions and their biogeochemical cycles (Moutinho, 2006). These factors tend to lead to more drastic alterations over longer periods of time, with losses of suitable areas for the occurrence of humid forests. A reduction of suitable areas for the occurrence of humid forests (e.g., the Amazonian rainforest) was predicted in our study (see Figure 1), with the expansion of suitable areas for the occurrence of SDTFs specialist trees. In recent studies, long-term experiments in the Amazon rainforest, excluding rainwater on the ground, Phillips et al. (2010) verified the death of several species due to prolonged drought events. The replacement of rainforests by vegetation types with savanna and deciduous characteristics has been proposed by numerous authors as a probable result of global climate changes (Moutinho, 2006; Pennington et al., 2006), and argues in favor of increases of areas with climatic conditions favorable for the occurrence of SDTFs in future scenarios.

Biological aspects were not evaluated in the present study, but deserve highlight on potential occupation of plant species in relation to climate changes (Colombo and Joly, 2010). One of the greatest challenges that will face mankind in the near future will be the development of conservation strategies that function on a progressively warmer and drier planet (Moutinho, 2006). Hence, ecological observations and models on future climatic changes that can take into account the temporal dynamics of ecosystems will be necessary for the development of conservation strategies appropriate to each vegetation type

(Mayle et al., 2007). According to Peterson et al. (2001), species can disperse, acclimate, adapt or become extinct in response to climatic changes. Our ENM also indicate that areas with high environmental suitability for occurrence of the three focal species in present climatic scenario can become reduced and/or disappear in future (2080), because of the severe and longer drought that can increases aridity and desertification in some regions, mostly occupied by northeastern region of the country (e.g., Caatinga biome). Studies like that of Werneck et al. (2011), in which the authors modeled the paleodistribution of SDTFs using *A. colubrina,* have demonstrated species migrations in response to climate changes. These authors noted the expansion of SDTFs after the last glacial maximum in the Pleistocene era until the present time. Following this same pattern, our study indicated that future climatic changes will continue to favor a general expansion of these forests. Additionally, the results contradicts to Pennington et al. (2006), who postulated that dry forests rather than open savanna may be replaced by humid tropical forests in the neotropical region, with repercussion in the traditional view of 'Refugium Theory', in which forest-savanna mutual interplay occurred during glacial maxima.

Werneck et al. (2011) detected areas of SDTFs in the (remnant) Caatinga biome that have been stable since the last glacial maximum. These areas apparently were refugia that sheltered high genetic diversity and endemism during the Pleistocene until the present time (Werneck et al., 2011). These stable nuclei deserve special conservation considerations that will help maintain their ecological and evolutive processes, but our modeling predicts that the suitability in such sites will be greatly reduced in the near future. Long-term multidisciplinary studies are necessary to make reliable predictions of the plant's adaptation strategies and responses to climate changes in SDTFs at community level. Considering that only 3.02% of the SDTFs in Brazil are included within officially established conservation areas (Sevilha et al., 2004) and the high deforestation rate (Miles et al., 2006), the future of these forests appears quite tenuous. As such, public policies to minimize the effects of climate change on the biodiversity found within SDTFs must be undertaken rapidly.

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